BROADBAND/MULTI-BAND CIRCULAR ARRAY ANTENNA

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CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application claims priority to copending U.S. provisional application entitled, "Broadband/Multiband Circular Array Antenna," having serial number 60/480,384, filed June 20, 2003, which is entirely incorporated herein by reference.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

[0002] The U.S. government has a paid-up license in this invention and the right in limited circumstances to require the patent owner to license others on reasonable terms as provided for by the terms of F04611-01-C-0008 awarded by the Air Force Flight Test Center, Edwards AFB, California 93524.

TECHNICAL FIELD

[0003] The present invention is generally related to radio-frequency antennas and more particularly, circular array antennas having a directional beam for omnidirectional coverage.

BACKGROUND

[0004] The array antenna is a class of antenna that employs multiple element antennas to form a fixed or steered directional beam to perform essential functions in wireless telecommunications, radar, navigation, guidance, electronic warfare, *etc.* Array antennas that can both transmit and receive can be classified as: (1) phased array antennas in which every element is connected to the transmitter/receiver via a network to achieve a certain amplitude and phase distribution needed for beam forming; (2) switched-element array antennas, which achieve beam shaping and beam steering by turning on or off certain elements; (3) Yagi-Uda array antennas in which most array elements are parasitically coupled to one or a few driven elements.

[0005] Existing array antennas are predominately of the first two types, *i.e.*, phased arrays and switched-beam arrays, and in particular linear and planar phased arrays. Unfortunately, phased array and switched-beam array antennas are expensive, bulky, and complex as compared with the Yagi-Uda array antennas. As a result, as pointed out by King *et al.* (R. W. P. King, M. Owens, and T. T. Wu, "Properties and applications of the large circular resonant dipole array," *IEEE Transactions on Antennas and Propagation*, Vol. 51, No. 1, pp. 103-109, January 2003), perhaps the most useful array antenna is the Yagi-Uda array antenna. The Yagi-Uda antenna, invented eight decades ago (H. Yagi and S. Uda, "Projector of the sharpest beam of electric waves," *Proc. Imperial Academy of Japan*, Vol. 2, p. 49, Tokyo, 1926), has gone through considerable development to evolve into a variety of forms and functionalities.

[0006] The class of Yagi-Uda array, as exemplified in a linear array **10** shown in **FIG. 1**, consists of *n* dipole elements, which include a driven element **11** connected with the transmitter and/or receiver, as well as a parasitically excited reflector **12** and (*n*-2) directors **13**. Reflector **12** and directors **13** are positioned to reflect and reinforce, respectively, the electromagnetic wave emitted from the driven element **11**

by parasitic resonance action, resulting in a beam in the direction of the **Z**-axis with polarization parallel to the **X**-axis. The usefulness of the Yagi-Uda array is due to its low cost, lightweight, and low wind resistance. Familiar applications include VHF/UHF antennas for television as well as other broadcasts and communications.

[0007] The circular Yagi-Uda array was first envisioned in the patent application of Yagi filed as far back as 1926 (U.S. Patent No. 1,860,123, issued May 24, 1932). As shown in **FIG. 2**, a circular array **20** comprises a driven element **21** at the center (*i.e.*, the origin of the rectangular **X-Y-Z** coordinates) and multiple parasitically excited elements **25** on the **X-Y** plane about the **Z**-axis. Parasitically excited elements **25** are located along a circle having a radius, *r*, of about ¼ λ, where λ denotes the operating wavelength. The driven element **21** and the parasitically excited elements **25** are arranged in a direction substantially parallel to the **Z**-axis to have a substantially similar polarization. Additional concentric rings of parasitic elements at radii of ½ λ, 3/4 λ, *etc.* were also indicated in the Yagi patent. By controlling the parasitic elements **25**, a beam can be formed in the **X-Y** plane and electronically steered about the Z-axis.

[0008] In the early 1970s when the need for low-cost arrays arose and the practical advantages of the Yagi-Uda array were amply demonstrated, engineers began to investigate circular Yagi-Uda arrays. Unfortunately, the efforts in developing circular Yagi-Uda arrays have been much less successful than those for the linear Yagi-Uda arrays and engineers invariably employed monopole antennas as the array elements, as shown in **FIG. 3**. A circular array **30** comprises a driven monopole element **31** at the center and multiple parasitically excited monopole elements **35** located along a circle centered at the driven monopole element **31**. The parasitically excited elements **35** are monopoles on top of a conducting ground plane **32**. Electronic beam steering is achieved by varying the individual input impedance of the parasitic elements **35**.

[0009] Early linear Yagi-Uda array antennas in the 1920s had a very narrow bandwidth of less than 1%. It was only a gradual shift in the design methodology from the concept of linear parasitic resonance arrays to the concept of traveling wave antennas that led to the enhancement of bandwidth to 10%, 20%, and 100% over the following decades, and finally to over 1000% in the 1960s.

[0010] Similarly, prior-art approaches for circular Yagi-Uda arrays have been predominantly based on the concept of resonance between driven and parasitic array elements as well as lumped-element circuits to control the RF impedance, thus the beam.

[0011] These prior-art approaches result in antennas limited in their operational frequency and bandwidth. The antennas are narrow-banded, a limitation rooted in the inherently narrow-band resonance mechanism employed for the parasitic electromagnetic coupling in these designs. The resonance mechanism is sensitive to the location and length of these element antennas in terms of the operating wave-length (λ), thus making the array narrow-band. These prior-art techniques are also handicapped by their circuit-based design approaches for the antenna structure. Thus, prior-art antenna designs are not practical or even applicable at frequencies above UHF (ultra-high frequency – from 300 MHz to about 1 GHz), where wave phenomena become manifest and prominent. The use of resonant monopoles for both driven and parasitic elements also leads to an undesirably high profile for the array.

SUMMARY

[0012] One embodiment is a broadband/multiband circular directional array antenna comprising a driven omnidirectional traveling-wave antenna element coupled to a transceiver via a feed network and a plurality of surface-waveguide elements concentrically and symmetrically positioned about and spaced from the driven omnidirectional traveling-wave antenna element. The surface-waveguide elements are configured to receive control signals configured to alter surface-waveguide characteristics to steer the array beam.

[0013] Although the disclosed embodiments are well suited for electronic beam-steered arrays, the broadband/multiband circular array antenna is readily applicable to various antenna types such as reciprocating beam antennas, fixed beam antennas, among others. The technique is amenable to a range of frequencies above UHF, where the wave nature of the antenna system predominates, as well as a range of frequencies below UHF, where a circuit type embodiment may be adequate.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] The present broadband/multiband directional antenna, as defined in the claims, can be better understood with reference to the following drawings. The components within the drawings are not necessarily to scale relative to each other; emphasis instead is placed upon clearly illustrating the principles of the antenna beam-steering and the related methods.

[0015] **FIG. 1** is a perspective view of a prior-art linear Yagi-Uda array.

[0016] **FIG. 2** is a perspective view of a prior-art circular Yagi-Uda array with a single driven element.

[0017] **FIG. 3** is a perspective view of a prior-art circular array of monopole elements on a ground plane with a single driven element.

[0018] **FIGs. 4A** and **4B** are, respectively, a top view and a side cross-sectional view of an embodiment of a small low-profile broadband/multiband circular array antenna.

[0019] **FIG. 5** is a schematic diagram showing an embodiment of a switching circuit that provides a control signal for a surface-waveguide element of the broadband/multiband circular array antenna of **FIGs. 4A** and **4B**.

[0020] **FIG. 6** is a side plan view with portions of an enclosure cut-away to reveal elements of an embodiment of a broadband/multiband circular array antenna.

[0021] **FIGs. 7A-7D** are drawings showing four embodiments of surface waveguides.

[0022] **FIG. 8** is a perspective view of an embodiment of broadband/multiband circular array antenna.

[0023] **FIG. 9** is a set of measured azimuthal radiation patterns at 1.525 GHz showing beam steering in the azimuthal plane for the of broadband/multiband circular array antenna of **FIG. 8**.

[0024] **FIG. 10A** is a set of measured azimuthal radiation patterns for the broadband/ multiband circular array antenna of **FIG. 8** showing beam steered to 0° at various frequencies in L and S bands.

[0025] **FIG. 10B** is a set of measured azimuthal radiation patterns for the broadband/ multiband circular array antenna of **FIG. 8** showing beam steered to 45° at various frequencies in L and S bands.

DETAILED DESCRIPTION

[0026] The present broadband/multiband directional antenna is described in further detail below. One embodiment is a small low-profile broadband/multiband circular array having an electronically steered directional beam for omnidirectional coverage. The array comprises a single driven broadband/multiband traveling-wave antenna element and multiple controlled surface-waveguide elements, which are symmetrically positioned around and adjacent to the driven element on an essentially circular circumference centered at the driven element. The array elements are located on a ground plane, which is, in general a reactive surface but can be an electrically conductive surface. The single driven element is connected via a feed network to a receiver and/or a transmitter. The driven element is a broadband/multiband traveling-wave antenna having an omnidirectional pattern, and preferably is also small and has a low profile, such as a mode-0 slow-wave antenna or a spiral-mode microstrip antenna.

[0027] Each surface-waveguide element is connected to, and controlled by, a switching circuit. Each surface-waveguide element presents two possible filtering states to the traveling wave: to pass or to reflect the incoming traveling wave. The RF (radio frequency) signal is isolated from the control circuit by low-pass filters. Switches, such as PIN diodes, are used to enable the surface waveguides to be electrically connected or disconnected to the ground plane, thus yielding binary states of filtering action. The switching circuit is generally on a microstrip or stripline circuit board enclosed by a box of conducting surfaces with shorting pins for suppression of RF leakage and higher-order modes. The switching circuit is connected to and controlled by an array beam steering computer.

[0028] The array provides a directionally controllable antenna beam with broadband/multiband frequency performance in a low-profile design that is both practical and economical to produce and maintain.

[0029] Although the disclosed embodiments are primarily suited for electronic beam-steered arrays, the broadband/multiband circular array antenna is readily applicable to fixed beam arrays, in which case fixed surface waveguides of much simpler configuration can be used. Note that none of the control circuits, *etc.*, are needed for a fixed beam array antenna. The technique is amenable to frequencies above UHF,

where the wave nature of the antenna system predominates, as well as at lower frequencies where a circuit type embodiment may be adequate.

A Broadband/Multiband Circular Array Antenna

[0030] **FIGs. 4A** and **4B** show, respectively, a top plan view and a front plan view for an embodiment of a small low-profile broadband/multiband circular array **100** embodying the principles of the present directional antenna. The array **100** comprises a single driven element **120** in the center and multiple controlled surface-waveguide elements **130**, such as **130a**, **130b**, **130c**, and **130d**, on an essentially circular circumference. Surface-waveguide elements **130a**, **130b**, **130c**, and **130d** are positioned adjacent to ground plane **110**, which is in general a reactive surface (to be discussed later) but can be an electrically conducting surface that is essentially planar and symmetrical about the Z-axis. As shown in **FIG. 4B**, the single driven element **120** is connected via feed network **150** to a transceiver **160**. In alternative embodiments (not shown), a receiver or a transmitter may replace the transceiver **160**.

[0031] The driven element **120** centered at the **Z**-axis is a broadband/multiband traveling-wave antenna, which produces an omnidirectional radiation pattern about the **Z**-axis. Preferably, the broadband/multiband driven element **120** is also small and has a low profile along the **Z**-axis, such as a mode-0 slow-wave antenna (J. J. H. Wang and J. K. Tillery, "Broadband Miniaturized Slow-Wave Antenna," U.S. Patent Number 6,137,453, October 24, 2000) or a spiral-mode microstrip antenna (J. J. H. Wang and V. K. Tripp, "Multioctave Microstrip Antenna," U.S. Patent Number 5,313,216, May 17, 1994).

[0032] The surface-waveguide elements **130** are positioned symmetrically on an essentially circular circumference, and are adjacent and close to the driven element **120**. Although only four surface waveguides **130a**, **130b**, **130c**, and **130d** are shown, a larger number of surface waveguides can be used to obtain more beams and/or narrower beams as may be desired. The driven element **120** is made as small as possible. However, the low-profile and broadband/multiband requirements, constrained by the present state of the art, dictate that the diameter of an enclosure surrounding the driven element **120** is likely to be larger than $\lambda/8$ at the low end of the operating frequencies.

[0033] Without loss of generality, the theory of operation can be explained by considering the case of transmit; the case of receive is similar on the basis of reciprocity. Referring to **FIGs. 4A** and **4B**, the traveling wave **125** is emitted radially outward from the center of the driven element **120**, which is a traveling wave antenna. The surface waveguides **130a** through **130d** each present, as a filter, two possible states to traveling wave **125**. A first filter state passes the traveling wave **125**. A second filter state reflects the traveling wave **125**. In the embodiment illustrated in **FIG. 4B**, a beam would be radiated in the direction of the X-axis if the surface-waveguide elements **130a** and **130c** are in the first and second filter states, respectively (*i.e.*, surface-waveguide element **130a** passes and surface-waveguide element **130c** reflects the incident traveling wave **125**, respectively). Surface-waveguide elements **130b** and **130d**, which are removed from the side plan view of **FIG. 4B** to reveal driven element **120** and traveling waves **125**, can be in either the pass or the reject state, but should be of an identical state to ensure symmetry of the beam.

[0034] A switching circuit 200 controls the state of each surface waveguide filter. Switching circuit **200** is substantially surrounded by enclosure **140**, which is generally placed adjacent to the ground plane **110**. Switching circuit **200** is connected with each surface-waveguide element **130** by conducting wires **135** passing through via holes **112** within the ground plane **110**. Each of the conducting wires **135** is electrically isolated from ground plane **110**. Feed network **150**, which couples driven element **120** to transceiver **160**, is generally a balun, which transforms the impedance and transmission mode of driven element **120** to match those of transceiver **160**. Surface traveling waves **125**, while supported on a reactive ground plane **110** in the described embodiment, can also be supported on a purely conducting and essentially planar surface.

[0035] **FIG. 5** shows schematically an embodiment of an individual switching circuit **200**, one of which is connected to each respective surface-waveguide element **130a** through **130d** (**FIGs. 4A** and **4B**) via conducting wires **135** (**FIGs. 4A** and **4B**). Four such switching circuits **200**, one for each surface-waveguide element **130**, are supplied. A control signal **205** processed by switching circuit **200** and applied at output terminal **250**, which is connected to conducting wire **135**,

determines the filtering state of a corresponding surface-waveguide element **130**. Control signal **205** is provided by an array beam-steering computer or some other suitably configured beam-steering mechanism, and is coupled to the switching circuit **200** at input terminal **210**. In the embodiment illustrated in **FIG. 5**, control signal **205** is current limited by resistor R_1 and filtered by the parallel combination of R_2 and C_1 before being passed to buffer **220**. Buffer **220** amplifies control signal **205** before forwarding the control signal **205** to bipolar driver **230**. The output of bipolar driver **230** is coupled to low-pass filter **240** via current limiting resistor R_3. Bipolar driver **230**, by way of bias voltages Vcc and Vee, controllably turns on or off series connected PIN diodes CR_1 and CR_2 coupled between the output of low-pass filter **240** and ground.

[0036] A RF signal received by or transmitted from transceiver **160** (**FIG. 4B**) is isolated from the switching circuit **200** by low-pass filter **240**, which includes capacitor C_4 and inductor L. Output signal **255** controllably connects or disconnects a corresponding surface-waveguide element **130** coupled to output terminal **250** with the ground plane **110** (**FIG. 4**). When a respective surface-waveguide element **130** is electrically isolated from the ground plane **110**, an incident omnidirectional traveling wave **125** is generally not affected and passes through it. When a respective surface-waveguide element **130** is electrically coupled to the ground plane **110**, an incident traveling wave **125** is generally reflected by the surface-waveguide element **130**. In practice, each surface-waveguide element **130** has both transmission and reflection properties, which are expressed by its complex reflection coefficient. Generally, a surface waveguide is considered to pass a wave if its predominant feature is transmission rather than reflection. In addition, there are mutual electromagnetic couplings between the driven element **120** and the surface-waveguide elements **130**. Thus, a directional beam results from the combined effects of these interactions.

[0037] To generate a beam in a particular direction, there are a number of filtering states that can accomplish it. In the case of the configuration of **FIGs. 4A** and **4B** having four surface-waveguide elements **130**, a total of 8 beams can be generated. For each beam there is more than one feasible filtering states, which have the general directionality but exhibit different features in terms of back lobe and other pattern variations.

[0038] For example, let us consider the case of transmit and designate two states, S and O, for each of the surface-waveguide elements **130**, that is, **130a**, **130b**, **130c**, and **130d**. Filter state S passes the traversing traveling wave **125** from driven element **120**. Filter state O reflects the traversing traveling wave **125** from driven element **120**. To generate a beam directed along the **X**-axis over a desired frequency band in the operating frequency range of the array **100**, surface-waveguide elements **130a**, **130b**, **130c**, and **130d** can have the following two states (1) S, O, O, O; (2) S, S, O, S; respectively. If the broadband/multiband circular array **100** has more surface-waveguide elements **130** than the four shown in **FIG. 4A**, for each beam there will be more possible combinations of filtering states.

[0039] **FIG. 6** is a front plan view of a broadband/multiband circular array **600** with transmission-line antennas **630**, **632** serving as surface-waveguide elements. The array **600** comprises a single driven traveling-wave element antenna **120** in the center and multiple controlled transmission-line antennas **630**, **632** arranged along two substantially circular concentric circumferences similar to the single circumference arrangement in the top view in **FIG. 4A**. Transmission-line antennas **630**, **632** are positioned adjacent to ground plane **610**, which is in general a reactive surface or an electrically conducting surface that is essentially planar and symmetrical about the **Z**-axis. As shown in **FIG. 6**, the single driven element **120** is connected via feed network **150** to a transceiver **160**. In alternative embodiments (not shown), a receiver or a transmitter may replace the transceiver **160**. The driven element **120** centered at the **Z**-axis is a broadband/multiband traveling-wave antenna, which produces an omnidirectional radiation pattern about the **Z**-axis.

[0040] The transmission-line antennas **630**, **632** are positioned symmetrically on two essentially circular concentric circumferences, and are adjacent and close to the driven element **120**. The driven element **120** is made as small as possible. However, the low-profile and broadband/multiband requirements, constrained by the present state of the art, dictate that the diameter of an enclosure surrounding the driven element **120** is likely to be larger than $\lambda/8$ even at the low end of the operating frequencies.

[0041] Without loss of generality, the theory of operation can be explained by considering the case of transmit; the case of receive is similar on the basis of reciprocity. The traveling wave **125** is emitted radially outward from the center of the

driven element **120,** which is a traveling wave antenna. The transmission-line antennas **630**, **632** each present, as a filter, two possible states to an incident traveling wave **125**. A first filter state passes the traversing traveling wave **125**. A second filter state reflects the traversing traveling wave **125**.

[0042] The state of each surface waveguide filter is controlled by a switching circuit **200** surrounded by conducting enclosure **140**, which is generally placed adjacent to ground plane **610**. Enclosure **140** substantially surrounds switching circuit **200**, except for the vias **612** similar to those for the ground plane **610**, which serve to pass the wires connecting surface waveguides **630**, **632** and control circuit **200**, to prevent undesired RF coupling and interactions with array elements outside the enclosure **140**. In the illustrated embodiment, enclosure **140** is a conducting box that includes the ground plane **610** if ground plane **610** is conducting. When the ground plane **610** is reactive enclosure **140** must have its own conducting enclosure rather than relying on the ground plane **610**. Switching circuit **200**, which can be implemented on a microstrip or stripline circuit board, is connected with each transmission line antenna **630, 632**. Switching circuit **200** receives beam-steering control signals via cable **202**. The control wires for the transmission-line antennas **630**, **632** pass through via holes **612** within the ground plane **610**.

[0043] In addition to showing how the transmission-line antennas **630**, **632** are connected to switching circuit **200**, the removed portions of enclosure **140** reveal mode suppressors **642** within enclosure **140** that surround switching circuit **200**. Mode suppressors **642** are generally placed around the switching circuit **200** to ensure that higher-order modes are suppressed and evanescent, and thus the RF energy inside enclosure **140** propagates in the dominant mode on the transmission lines in the circuit board. Mode suppressors **642** can be a group of conducting pins, as shown in **FIG. 6**, connecting the ground plane **610** to the lower inner surface of the enclosure **140**. The conducting pins should enclose the switching circuit **200** with sufficient density. Specifically, the distance between adjacent pins should be less than ¼ λ at the highest operating frequency of the broadband/multiband circular array **600**. In addition, the volume enclosed by the mode-suppressing conducting pins should be small enough to suppress cavity resonance. Accordingly, RF disturbances, should they occur, will be local and evanescent.

[0044] The broadband/multiband feature of the surface waveguides is rooted in the physics of the surface wave, which can be supported on a generally planar and preferably reactive surface. **FIGs. 7A** through **7D** show multiple tunable surface waveguide arrangements. **FIG. 7A** shows a surface-waveguide element **130** consisting of a dielectric layer **236** on top of a conducting surface **235**. By judiciously varying the distributive dielectric constant of the dielectric layer **236**, the impedance property of the surface waveguide can be varied to control the directional property of the wave and thus the radiation pattern.

[0045] **FIG. 7B** shows another example of surface-waveguide arrangement **730** consisting of a set of conducting plates, rods, or corrugated structures **237** adjacent to conducting surface **235**. The choice of the thickness of the conducting plates, the diameter of the rods, their heights and relative spacing, *etc.*, of the corrugated structures within the set **237** is governed by the well established theory and practices on surface waveguides as will be discussed under a latter section entitled "Theory." The complex transmission and reflection property of the surface-waveguide **730** can be individually tuned and controlled by varying the impedances at the gaps (at the vias of the ground plane **235**) between the corrugated structures **237** and the conducting surface **235**. In addition to tuning the elements of set **237** at the gaps, the relative height, spacing, and position of the elements of set **237** can also control the directional property in elevation of a traveling wave incident upon the elements of the **237** so that the beam peak can be made closer to or further from the horizontal plane (the **X-Y** plane).

[0046] **FIG. 7C** shows a second example of a surface-waveguide arrangement **740** consisting of another set of conducting plates, rods, or corrugated structures **238** adjacent to conducting surface **235**. The theory, function, and operation of set **238** and surface-waveguide arrangement **740** are similar to those for set **237** and surface-waveguide arrangement **730**. As described above regarding set **237** (**FIG. 7B**), the conducting plates, rods, or corrugated structures within set **238** can be individually tuned. In addition to the design flexibility offered by controlling the impedance of individual elements of set **238**, the relative height, spacing, and position of the elements of set **238** can be adjusted to further control the directional property of a traveling wave incident upon set **238**.

[0047] **FIG. 7D** shows a third example of a surface-waveguide arrangement **750** consisting of a third set of conducting plates, rods, or corrugated structures **239** adjacent to conducting surface **235**. The theory, function, and operation of set **239** and surface-waveguide arrangement **750** are also similar to those for set **237** and surface waveguide arrangement **730**. As with sets **237, 238** above (**FIGs. 7B** and **7C**), each of the conducting plates, rods, or corrugated structures within set **239** can be individually tuned. In addition, the relative height, spacing, and position of the elements of set **239** can be adjusted to control the directional property of a traveling wave incident upon set **239**.

[0048] The choice for the thickness of the plates or the diameter of the rods, as well as their heights and the spacing between adjacent elements, in each of the example arrangements **730, 740,** and **750** illustrated in **FIGs. 7B** through **7D** is determined using theory described and referenced in the next section entitled "Theory." While the illustrated embodiments include symmetrically arranged and evenly spaced elements within sets **237, 238,** and **239**, respectively, other embodiments are also implied for use in the broadband/multiband circular array antenna.

[0049] A switch corresponding to each surface-waveguide element **130, 630, 632** (*e.g.*, sets **237, 238, 239** of conducting plates, rods, or corrugated structures, such as transmission line antennas) bridges or leaves open the gap electrically to offer two states of filtering corresponding to each surface-waveguide element to incident traveling waves **125**. Practical implementation of the binary states controlled by the switching circuit **200** in the case of the surface waveguide has been discussed earlier by way of **FIGs. 5** and **6**.

Theory

[0050] The present circular-array antenna is based on the concept of radial traveling-wave arrays and takes advantage of the inherent broadband nature of surface wave propagation by using surface waveguides that have broadband binary filtering capability electronically controlled by switches, such as PIN diodes and/or MEMS (micromachined electromechanical system) switches.

[0051] Without loss of generality, the theory of operation can be explained by considering the case of transmit; the case of receive is similar on the basis of reciprocity. Referring to **FIGs. 4A** and **4B**, the traveling wave **125** is emitted radially outward from the center of the driven element **120**, which is a traveling wave antenna. In order to generate omnidirectional RF radiation near the surface of the ground plane **110** and to achieve broadband/multiband operation, the launched traveling wave **125** is preferably a surface wave propagating along, and intimately bound to, the ground plane **110**, as well as the surface-waveguide elements **130**. The four surface-waveguide elements **130 (130a, 130b, 130c**, and **130d)** serve as binary filters, which pass or reflect the incident traveling wave **125** as commanded by respective switching circuits **200 (FIG. 5)**. Discussions on traveling-wave antennas, traveling-wave structures, reactive surfaces, and surface waveguides can be found in the following textbooks: C. H. Walter, *Traveling Wave Antennas*, McGraw-Hill, New York, NY, 1965 and R. E. Collin, *Field Theory of Guided Waves*, second edition, IEEE Press, IEEE, New York, 1991.

[0052] The surface waveguide element sets **237, 238, 239 (FIGs. 7B** through **7D)**, which can be viewed as an aggregate of transmission line antennas or a corrugated surface, are filters of the distributed type, versus filters made of lumped elements commonly employed at lower frequencies. Transmission line antennas are a section of the transmission line supporting the traveling surface wave. The broadband/multiband feature of these surface-waveguide elements is rooted in the physics of the surface wave, which can be supported on a generally planar and preferably reactive surface. A surface wave can also be supported on a purely conducting and essentially planar surface. Analysis of a surface wave along a plane interface leads to a TM (transverse magnetic) wave, which has a magnetic field perpendicular to the direction of propagation and parallel to the plane surface. The TM mode also has electric fields perpendicular to the plane surface and in the direction of propagation. The corrugated surface is a well-known surface waveguide for the TM surface wave. The corrugated surface waveguide can either pass or reject the surface wave, depending on whether it is connected or disconnected with the ground plane.

[0053] The surface waveguide can support a surface wave with no low-frequency cutoff, and has only a minimal number of discrete modes. Generally, and preferably, the traveling wave is a slow wave having a phase velocity less than that of light. The selection of the surface waveguide is based on the type of surface wave desired and the controllable binary-filtering feature possessed.

[0054] Although there are many forms of surface waveguides, the present broadband/ multiband circular array antenna uses those with variable filtering functionality, which is controllable electronically. A dielectric-layered surface waveguide (**FIG. 7A**) is more difficult to switch or vary, therefore not easily or readily amenable to switching actions. On the other hand, conducting plates, rods, or corrugated structures in sets **237**, **238**, **239** in **FIGs. 7B** through **7D** are spaced at a very small distance apart from the conducting surface **235**. Thus, the surface-waveguide elements in **FIGs. 7B** through **7D** have binary states dictated by shorting or opening the small gap with a device such as a diode, thereby connecting and disconnecting the separate conducting plates, rods, or corrugated structures across sets **237**, **238**, or **239** with the conducting surface **235**. Theory for the surface-waveguide elements in **FIGs. 7B** through **7D** predicts broadband filtering action in both states. Measurements also showed that the number of conducting plates or rods can be as few as one; like a single-section filter consisting of one section using a single inductor (L), capacitor (C) or an L-C section, consistent with filter theory (G. Matthaei, L. Young, and E. M. T. Jones, *Microwave Filters, Impedance-Matching Networks, and Coupling Structures*, McGraw-Hill, New York, 1964, reprinted by Artech House, Norwood, MA in 1980).

[0055] Although the structurally suspended configurations (between the individual elements of sets **237**, **238**, and **239** and conducting surface **235**) illustrated in **FIGs. 7B** through **7D** are feasible, a more practical embodiment, illustrated in **FIG. 6**, shows transmission-line antennas **630**, **632** mechanically supported by the dielectric layer of the printed circuit board of the switching circuit **200**. Suitably positioned switches such as a PIN diode or a MEMS switch controllably couple each respective transmission line antenna **630**, **632** to ground plane **610**.

Experimental Verification

[0056] Extensive experimentation has been performed successfully for this broadband/multiband circular array antenna. **FIG. 8** is a perspective view of an embodiment of a model broadband/multiband omnidirectional circular array antenna **800**. In **FIG. 8**, a square disk-shaped mode-0 slow-wave antenna, which is approximately 2.5-inch × 2.5-inch square and approximately 0.75-inch tall, is used as the driven element **840**. Transmission line antennas **830** are arranged concentrically about driven element **840** on ground plane **810**. The ground plane **810** is conductive and simulates a mounting platform, such as the exterior surface of an airplane. Each of the transmission line antennas **830** extends through a respective via **812** in ground plane **810**. The transmission line antennas **830**, as illustrated and described above, are coupled to respective switching circuits **200 (FIG. 5)** in an enclosure obstructed from view by ground plane **810**.

[0057] The capability of electronic beam steering of this antenna is shown in **FIG. 9**, which displays steered azimuthal patterns measured for the breadboard model of **FIG. 8** at 1.525 GHz in an anechoic test chamber at Wang Electro-Opto Corporation. As can be seen, there are eight beams, which span the entire 360° for full azimuth coverage. The desired broadband and multiband performance of this circular array antenna **800** is demonstrated by the measured radiation patterns in **FIGs. 10A** and **10B**. **FIG. 10A** shows measured azimuthal patterns for the model of **FIG. 8** steered to 0° at various frequencies in the two operating frequency ranges, one in the L band and another in the S band. **FIG. 10B** shows similar broadband/multiband measured azimuthal patterns steered to 45°.

Variation and Alternative Forms of the Broadband/Multiband Circular Array Antenna

[0058] Although four surface-waveguide elements **130** are shown in the **FIGs. 4A**, **4B**, *etc.*, any number of surface-waveguide elements **130** can be chosen.

[0059] Although only four switchable broadband/multiband surface waveguides are shown in **FIGs. 7B** through **7D**, additional symmetrically positioned and concentrically arranged switchable broadband/multiband surface waveguide elements are also implied in this broadband/multiband circular array antenna.

[0060] Although PIN diodes are shown in **FIG. 5**, other switches such as a MEMS switch are also implied in this broadband/multiband circular array antenna.

[0061] If the desired angular range of beam scan is less than the full azimuth coverage of 360°, the antenna array may consist of surface-waveguide elements located along an arc equidistant from the driven traveling wave antenna whose omnidirectional pattern is narrowed accordingly. The angular span of the arc populated with surface-waveguide elements is similar to the range of beam steering in angular span.

[0062] Although the applications discussed have been for steered beams, the broadband/multiband circular array antenna is readily applicable to fixed-beam arrays. In the latter case, fixed surface waveguides of much simpler configuration can be used and the control circuits are removed.